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Details of the concept, analysis methods, and analysis results are available in the references cited. Suggestions for further analysis and verification tests of the system concept are included.

NAVIGATION CHECKPOINTING

USING HORIZON CORRELATION

by

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Final Report
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ABSTRACT

A summary of the analyses performed on the horizon correlation navigation checkpointing system is presented. This includes a brief description of the system concept and the analysis techniques used. The tradeoff and performance results are summarized and indicate that the theoretical feasibility of the system has been established. Details of the concept, analysis methods, and analysis results are available in the references cited. Suggestions for further analysis and verification tests of the system concept are included.

FOREWORD

This is the final report for research performed under contract number N00014-75-C-0639, project number NR387-076 entitled "Geographic Orientation". It summarizes the nature of the research project and the results obtained. Detailed technical discussions and results can be found in several technical reports issued under this contract. The work was performed by Dr. Gordon E. Carlson, Principal Investigator, and George L. Bair, Charles M. Benoit, Paul W. Sapp, and David L. Simmons, graduate students in Electrical Engineering, at the University of Missouri-Rolla, Rolla, Missouri. It was under the supervision of Dr. James S. Bailey, Director of the Geography Programs Branch, Earth Sciences Division, Office of Naval Research.

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NAVIGATION CHECKPOINTING
USING HORIZON CORRELATION

I. INTRODUCTION

Navigation capability is required for airborne vehicles so it is known where they are during a flight. For low-performance piloted vehicles at reasonable altitudes in fair weather, this navigation is performed by the pilot by visually identifying landmarks. This visual navigation becomes much more difficult at low altitudes and high velocities since the pilot does not have sufficient time to identify landmarks. Also it is unsatisfactory for flights in all weather and for vehicles without pilots. Consequently high performance vehicles utilize inertial navigation equipment to sense vehicle motions and integrate these to determine vehicle position. Errors in such navigation equipment cause the error in the knowledge of vehicle position to grow with elapsed flight time. Therefore, for most flight missions, periodic determination of vehicle position by automatic identification of terrain landmarks (navigation checkpoints) is required. This is accomplished by using an on-board sensor to sense a terrain feature and comparing (correlating) the sensed data with stored reference data.

A number of different systems have been previously identified and studied for performing correlation of sensed and reference terrain data. Several use down-looking mapping sensors (e.g. radar and I.R.) to obtain the sensed terrain data. At low altitudes, such sensors are only able to provide an image of a small area and thus there is a problem obtaining sufficient sensed image uniqueness so the checkpoint can be identified for other than very small vehicle offsets from the nominal flight path. Mapping sensors obtain their image from the characteristics of terrain cover and culture which means that this must be adequately modeled to produce suitable references.

A second method of sensing terrain data for correlation with reference data is to sense the terrain profile directly beneath the aircraft. This method has been extensively developed and is known by the acronym TERCOM (Terrain Contour Matching). This system requires only topographic data for reference generation and works equally well over a large range of altitudes. However: (1) it requires a large distance along the flight path to obtain a terrain profile with sufficient data content, and (2) the flight path characteristics must be known quite accurately during sensed profile acquisition so proper correlation can be accomplished.

Horizon profiles are different for different viewing locations. Therefore, they contain information which should be useful in determining an airborne vehicle's location. It has been proposed that

horizon profiles be sensed by an on-board sensor and compared with reference horizon profiles generated for viewing location in the neighborhood of the desired flight path to provide navigation checkpoint information. The horizon profiles used could be obtained from any azimuth angle with respect to the aircraft for which a sensor mounting position is available. Only a forward looking sensor has been considered in system analyses. However, similar system performance should be available with a sensor looking in any other direction.

One advantage of the proposed horizon profile comparison system is that sensed profiles covering a long horizontal dimension can be obtained rapidly with an azimuth scanning sensor. This eliminates the need for a long flight path increment to obtain a profile with significant data content. A second advantage is that automatic computer generation of reference profiles is possible and requires only topographic data. A third advantage occurs since reference profiles can cover a wider azimuth angular dimension than the sensed profiles. This means that profile identification is possible even if the aircraft heading is incorrectly known if the sensed profile is within the limits of the reference profile angular extent and the reference profile contains significant data over its extent.

A feasibility study of the proposed technique for obtaining navigation checkpoints has been performed. This study has considered several different implementation concepts and various system parameter tradeoffs. Tradeoff and performance analyses were done by using digital topographic data and computer simulation. A wide range of terrain roughness and vehicle flight characteristics were considered. These analyses have shown: (1) desirable sensor and system configuration characteristics, (2) effects of variations in system parameters, (3) system checkpointing performance for various terrain roughnesses, and (4) terrain roughness limitations on system operational capability. In addition existing radars have been identified which could be modified to obtain data for initial system concept tests.

The technical details of the system analyses performed have been presented in four technical reports and four papers.[1-8] The data presented in these reports and papers will be briefly summarized in this final report. The system and analysis techniques have evolved during the course of the project thus performance results summarized here are in general for final system configurations and analysis techniques as reported in Refs. 1 and 2. Parameter tradeoff data and system configuration considerations are in general summarized from the earlier technical reports references.

This report consists of three parts. The first briefly reviews the horizon correlation system concept and defines the system parameters of importance. Part two summarizes the analysis performed and results obtained. The last part indicates further system analysis and development which should be performed in the order that presently appears appropriate.

II. SYSTEM CONCEPT AND PARAMETERS

This section briefly reviews the concepts on which the horizon correlation checkpoint system is based. The locations from which the profiles are to be generated, the method of comparison, and various system and performance parameters are defined.

A. HORIZON CONCEPTS

Three different types of horizon-like profiles have been considered. The first of these were actual horizons defined by the maximum elevation angle to the terrain as a function of azimuth angle.[5,8] These proved to be usable for very low altitude flight below the surrounding terrain (i.e. in valleys).[8] However, at altitudes above the majority of the surrounding terrain, the actual horizon is obtained from terrain contributions at a large distance from the vehicle and thus insufficient elevation angle variation is available for reliable system performance.[5]

The second horizon-like profiles considered were fixed-range profiles defined by the maximum elevation angle to the terrain as a function of azimuth angle.[5] These profiles provide good system performance at higher altitudes since data from long ranges is excluded; however, they cannot be used at low altitudes since excessive shadowing of the terrain at the fixed range exists. It was determined that system operation was not greatly degraded as long as less than 40% of the fixed-range profile was shadowed and linear interpolation was used to fill in the shadowed portions of the profile,[4,5]

The third horizon-like profiles considered were range-limited horizons defined by the maximum elevation angle to the terrain within a defined range limit as a function of azimuth angle.[2] The range-limited horizons are essentially actual horizons at very low altitudes and fixed-range profiles at higher altitudes. Therefore, they provide similar system performance in these cases and can, in addition, be used at any altitude since shadowing and excessive ranges do not exist. This final report will only summarize performance results for a system utilizing range-limited horizons since this is the final system evolution. Such range-limited horizons will subsequently be referred to as horizons for simplicity.

B. SYSTEM CONCEPT

The system concept has been presented in detail in previous reports.[2,5,8] It is briefly summarized here.

The flight path is first planned by using topographic data for the mission area. The topography along the flight path is considered in identifying checkpoints which are close enough together so the desired flight path can be maintained and which have horizons with significant data content.

A set of reference horizons which would be seen from the airborne vehicle is generated for possible vehicle locations with spacing ΔR along a line array which crosses the flight path at each checkpoint location as shown in Fig. 1. For sketching convenience, the profiles are indicated as coming from a fixed range even though this would not be true in an actual case. The length of the line array required is established by expected vehicle cross-track position errors when it arrives at the checkpoint. This depends on vehicle dynamics, inertial navigator accuracy, guidance philosophy, and checkpoint separations and has not been analyzed. The reference horizons are generated with a digital computer from topographic data and correspond to the planned vehicle altitude and heading. The horizons consist of digital data and give elevation angle to the horizon as a function of azimuth angle with respect to flight path heading. The horizon sampling interval is determined by the sampling rate required to adequately describe the horizon and must also be compatible with onboard sensor capabilities. The reference horizons for a particular mission are stored on magnetic tape in the vehicle for inflight digital comparison with sensed horizons.

During flight, an on-board radar sensor is used to obtain sensed horizons as often as possible along the flight path (spacing = ΔS) as also shown in Fig. 1. As the sensed horizons are obtained, they are compared with all the reference horizons in the upcoming line array until identification is achieved with one of the reference horizons in that line array. The identification specifies the time at which the array is crossed (along-track position) and the location along the array at which it is crossed (cross-track position) as shown in Fig. 1. Actually, it may be desirable to make comparisons with several upcoming line arrays to avoid the possibility of mission abort due to a single erroneous line array mismatch.

A sensed horizon is generated with a narrower azimuth angular extent, θ_S, than the angular extent of the reference horizons, θ_R, as shown in Fig. 1. It is compared with horizon segments along the extent of the reference horizon to find the segment which it best matches. Thus horizon identification for position determination is achieved even if the airborne vehicle heading is incorrectly known provided the sensed horizon is within the limits of the reference horizon angular extent. The angular offset along the reference horizon at which identification occurs determines the vehicle heading.

The horizon comparisons indicated above are to be performed by the computer on-board the aircraft and must produce output values which are measures of how well sensed horizons and segments of reference

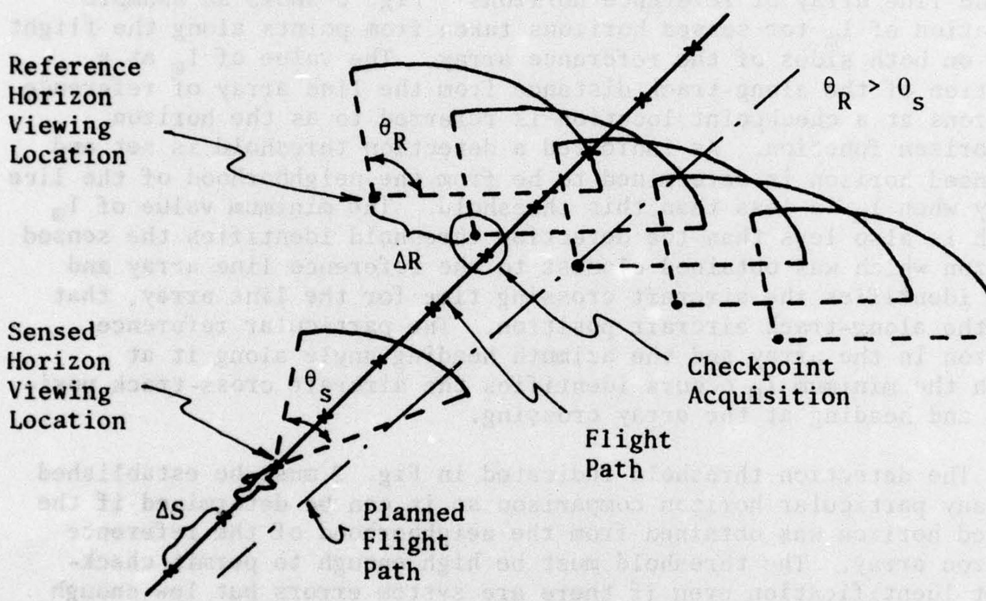

Fig. 1. Horizon Comparison System Concept.

horizons match. The comparison technique must be as simple as possible, consistent with good horizon selectivity, so that horizon comparisons can be made quickly. Various comparison techniques were studied.[8] Based on simplicity and performance, it was determined that comparison of a sensed horizon and a reference horizon segment is best performed by computing the integral absolute difference (IAD) between the sensed horizon with its mean value removed and the reference horizon segment with its mean value removed. Mean values are removed to eliminate sensitivity to sensed horizon mean value errors.

The minimum IAD value (I_m) computed for one sensed horizon and all segments of all reference horizons in one line array is used to determine if the sensed horizon was obtained from the neighborhood of the line array of reference horizons. Fig. 2 shows an example variation of I_m for sensed horizons taken from points along the flight path on both sides of the reference array. The value of I_m as a function of the along-track distance from the line array of reference horizons at a checkpoint location is referred to as the horizon comparison function. As indicated a detection threshold is set and a sensed horizon is determined to be from the neighborhood of the line array when I_m is less than this threshold. The minimum value of I_m which is also less than the detection threshold identifies the sensed horizon which was obtained closest to the reference line array and thus identifies the aircraft crossing time for the line array, that is, the along-track aircraft position. The particular reference horizon in the array and the azimuth heading angle along it at which the minimum I_m occurs identifies the aircraft cross-track position and heading at the array crossing.

The detection threshold indicated in Fig. 2 must be established for any particular horizon comparison so it can be determined if the sensed horizon was obtained from the neighborhood of the reference horizon array. The threshold must be high enough to permit checkpoint identification even if there are system errors but low enough so false identifications do not occur. The value of this threshold depends on the particular system parameters used, on the terrain roughness and on the magnitude of horizon and system errors expected. Threshold values thus must be determined for each line array used as a checkpoint.

C. SYSTEM AND PERFORMANCE PARAMETERS

System and performance parameters required to analyze and discuss the horizon correlation system are defined in this section. System parameters are: (1) reference horizon spacing along array, ΔR, (2) sensed horizon spacing along flight path, ΔS, (3) reference horizon length, θ_R, (4) sensed horizon length, θ_S, (5) horizon sample spacing, $\Delta\theta$, (6) nominal vehicle altitude, H_A, and (7) range limit, R_L.

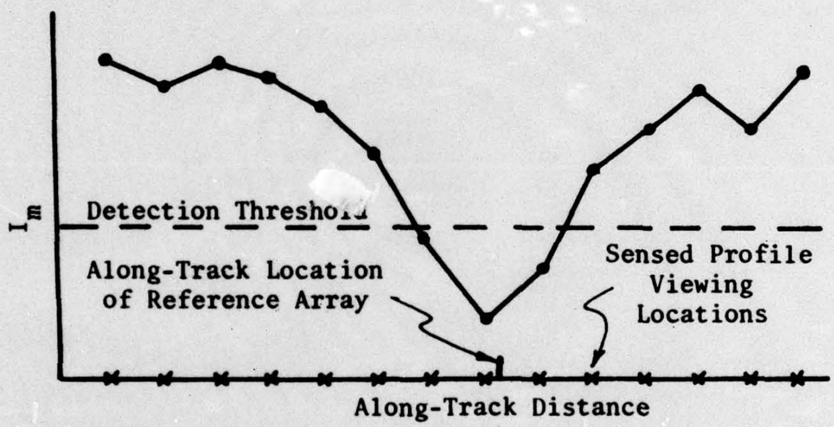

Fig. 2. Along-Track Position Identification.

Two major system error sources were considered in analyzing the system. These were: (1) random horizon error (standard deviation = σ_N), and (2) vehicle altitude error, ΔH.

In order to specify system performance, several performance indicators were defined. These include: (1) the standard deviation of the along-track position determination error, σ_x; (2) the standard deviation of the cross-track position determination error, σ_y; (3) the circular error probable, CEP, for the position determination error; and (4) the standard deviation of the heading error, σ_θ. The probability of detection, P_D, (probability of correct sensed profile identification) and the probability of false alarm, P_F, (probability of incorrect sensed profile identification) were used to establish the required selection threshold value and the maximum allowable random profile error and vehicle altitude error.

III. ANALYSIS AND RESULTS SUMMARY

This section presents a brief summary of the analysis techniques used and the results obtained. Considerable detail is available in the technical reports referenced.

A. ANALYSIS METHODS

Analysis of system performance was done by simulation of the horizon correlation operation for a checkpoint line array of reference horizons and sensed horizons obtained for a segment of the flight path on each side of the line array (5Km segments used for most analyses). The Monte Carlo technique was used with a uniform distribution of flight path location with respect to line array center location to obtain data for statistical determination of important system characteristics. These characteristics include: (1) the horizon comparison function, I_m, (2) the position determination errors, and (3) the heading determination errors. Random horizon errors and vehicle altitude errors were introduced to assess their impact on system performance and thus to determine their maximum allowable values. A number of different flight path segments over terrains with different roughnesses were analyzed.

Most of the analyses were performed by using actual terrain topographic data to generate reference and simulated sensed horizons. The terrain data used was for a range of different terrain roughness. The basic data used was digitized topographic data generated by the Defense Mapping Agency from standard 1:250000 scale United States Geological Survey maps. Linear interpolation between every third data point (190.5m spacing) was used to generate the terrain model to provide system simulations in reasonable computation time.[8]

Analyses were also performed with horizons generated from pseudo-terrain.[1] The use of pseudo-terrain permitted a more controlled analysis of the effect of terrain roughness on system performance. The statistical model used for generating the pseudo-terrain was developed by examining typical terrain height autocorrelation characteristics and generating a simple terrain height autocorrelation function to approximately match them.

The simple autocorrelation function defined used two correlation lengths to model the composite characteristic (shorter and longer term variations) of actual terrain.

The resulting approximately matching autocorrelation function was compared with several average sample terrain height autocorrelation functions and determined to match reasonably well. Later system

analyses indicated that the shorter correlation length of the analytic autocorrelation function (chosen to be 2/3 of the longer correlation length) appears to be too long for rougher terrain since all pseudo-terrain produced did not generate horizons with as much fine-grain variation as was apparent on horizons generated from actual terrain for comparison. Time and funding did not permit further optimization of the pseudo-terrain model; however, it was felt that the pseudo-terrain did represent actual terrain well enough to be used for system analyses.

B. RESULTS OBTAINED WITH ACTUAL TERRAIN DATA

Actual terrain data was used for many of the system analyses. These included system parameter tradeoffs as well as system performance analyses. For these analyses, a range limit of R_L = 5Km was used for the final system configuration. Vehicle altitudes, H_A, considered included 100m and 500m above the maximum terrain height beneath the flight path for flights above the majority of the surrounding terrain and reasonable heights above the valley floor for valley flights.

The frequency content of the difference between sensed and reference horizons near a match point was analyzed. Several different terrain roughnesses were considered. It was determined that a sample spacing of 1° is adequate for all terrain roughnesses.[5]

Tradeoff analyses were performed for the reference horizon spacing along a line array, ΔR, and the sensed horizon azimuth width, θ_S. It was determined that ΔR = 400m, and $\theta_S = 90°$ are good compromise parameters from the standpoint of performance and data storage requirements.[5] Actually a smaller value for ΔR will improve position determination accuracy (though not in direct proportion) and should be used if reference storage space permits. All performance results presented here are for the values of ΔR and θ_S indicated above.

System performance was determined in terms of: (1) the maximum allowable random horizon error standard deviation, σ_{NM}, (2) the maximum allowable vehicle altitude error, σH_M, (3) the along-track position determination error standard deviation, σ_x, (4) the cross-track position determination error standard deviation, σ_y, (5) the position determination circular error probable, CEP, and (6) the heading determination error standard deviation, σ_θ. Performance results were determined first for a system with no altitude error (i.e. no discrepancy between actual and planned vehicle altitude) and are summarized first.

The maximum allowable random horizon errors which give a probability of false alarm of less than 0.001 and a probability of detection of greater than 0.99 for flights above the majority of the surrounding terrain was determined to be greater than 0.1° for horizons with standard deviation, σ_p, greater than 1.1°. For relatively smooth terrain

(σ_p approx. 0.2° or 0.3°) the maximum allowable random horizon error is quite small and precludes practical system operation. The maximum allowable random horizon error increases rapidly (from approx. 0.1° to approx. 0.4°) as the horizon standard deviation increases from 1° to 2°. It was considerably less for the valley flights (0.1° at σ_p = 1.5°) and increases less rapidly with increasing horizon standard deviation.

The checkpoint position determination accuracy was analyzed and, except for relatively smooth terrain, gave a CEP of approximately 125m for flights above the majority of the surrounding terrain if the random horizon error was limited to be the smaller of the maximum allowable value or 0.25°. For the valley flights, the CEP is approximately 200m when the maximum allowable random horizon error is encountered. It should be noted that no interpolation between horizon comparison function points (200m spacing along-track and 400m spacing cross-track) was used so a large portion of the position error encountered is due to discrete match point quantization. Position performance could be improved by using interpolation.

The heading determination standard deviation obtained is approximately 1.75° to 2° for all cases without random horizon errors. Random horizon errors only have minimal effect on heading determination for flights above the majority of the surrounding terrain but increase the heading determination standard deviation to approximately 2.5° to 3° when maximum allowable values are considered for valley flights. Heading determination accuracy could be improved with interpolation and multiple measurements.

If the vehicle is not flying at the planned altitude for which reference horizons were generated, then reference and sensed horizon differences result. The effect of such altitude errors was analyzed. They produce little position or heading determination performance degradation in most cases if held within practical limits. They do reduce the maximum allowable random horizon error. For reasonable maximum random horizon errors, it was determined that altitude errors of ±100m or greater could be tolerated in most cases. A couple of cases were exceptions where the maximum altitude errors which could be tolerated were in the neighborhood of 40m to 50m.

All the system analyses used profile data with very fine amplitude quantization so performance obtained was affected only by system characteristics. In an actual system, it is desirable to use as coarse an amplitude quantization as possible to limit the storage required for reference profiles and to increase computation speed. The effect of quantization was analyzed by repeating simulations with varying degrees of quantization for selected analysis cases. It was determined that the computer wordlength can be as small as 6 bits without any significant effect on system performance.[5]

The system parameters and error limits obtained with the performance analyses were used to establish initial horizon sensor requirements and characteristics.[5] A K_u-band (17GHz) radar was selected with

a 1° azimuth beamwidth (based on required sample spacing) and a 3° monopulse elevation beamwidth. The scanning mechanization selected uses an elevation scan for each sensed profile which follows the previously sensed profile so off-boresight measurements of the difference of a sensed profile from the previously sensed profile can be made. This mechanization has moderate complexity and permits a relatively narrow elevation beamwidth to be used to increase accuracy and reduce the transmitted power requirement. Other radar parameters selected are: (1) peak transmitter power = 20Kw, (2) pulsewidth = 0.1 sec., (3) pulse repetition frequency = 7500 pps, and (4) scan time = 0.75 sec. Performance is not impaired by fog or clouds and: (1) rainfall is not a serious constraint on performance for very rough terrain, (2) rainfall of greater than moderate to heavy is detrimental to performance for rough terrain, and (3) light to moderate rainfall will not decrease performance for moderately rough terrain. Subsequent discussions with Syracuse Research Corporation indicated that it would probably be advantageous to use a phase monopulse radar like that presently implemented in the A6 aircraft since it provides similar performance with similar parameter requirements and less scan complexity.

The system analyses indicated above were performed with two radar sensor idealizations. These were: (1) horizons were obtained from a stationary viewing location, and (2) the radar azimuth beamwidth was infinitesimal. It was felt that these idealizations would not greatly affect the system feasibility and performance results. Analyses were performed with selected analysis cases to verify this conjecture and to provide a determination of radar azimuth beamwidth requirements.[2]

The analysis of the effect of nonstationary horizon viewing locations was performed by using an assumed vehicle velocity of 260m/sec and a one direction radar scan time of 0.75 sec. Results indicate that system performance is basically the same as determined for horizons from stationary viewing locations as long as reference horizons are generated for moving viewing locations determined by the planned vehicle velocity and sensor scan rate.

The analysis of the effect of a finite sensor beamwidth was performed by developing a suitable system model and considering sensor beamwidths from 0° to 4°. Cases were considered for several terrain roughnesses and for reference horizons generated with either the sensor beamwidth or a beamwidth of 0°. Results indicate that system performance is basically the same as determined for horizons generated with sensor beamwidths of 0°. Performance results were not greatly different between cases where the reference horizons were generated with the sensor beamwidth and cases where the reference horizons were generated with a beamwidth of 0°. Therefore, reference horizon generation does not need to consider sensor beamwidth which provides generation simplification in a practical case. Sensor beamwidths of 2° are certainly feasible and 4° sensor beamwidths are probably usable.

Sensor beamwidths of 2° or 4° would reduce the antenna length requirement (0.9m) defined by the 1° beamwidth indicated above to 0.45m or 0.225m respectively.

C. RESULTS OBTAINED WITH PSEUDO-TERRAIN DATA

Similar system analyses to those performed with actual terrain data were performed with the pseudo-terrain developed to indicate the validity of using the pseudo-random terrain and to provide a more controlled analysis of the effect of terrain roughness.[1] Additional analyses were then performed to determine the effect of varying several system parameters.[1]

System performance was analyzed for a baseline system with the following system parameters: (1) sensed horizon length, $\theta_S = 90°$, (2) sensed horizon viewing location spacing along the flight path, $\Delta S = 200m$, (3) reference horizon viewing location spacing along a line array at the checkpoint location, $\Delta R = 400m$, (4) horizon range limit, $R_L = 5m$, and (5) vehicle altitude, $H_A = 100m$ above the maximum terrain height beneath the flight path. Performance results were obtained for each of five flight paths and averaged to provide average system performance as a function of terrain roughness.

System performance in terms of position and heading determination errors were found to be relatively insensitive to terrain roughness. The values obtained for these errors were a position CEP of approximately 135m and a heading standard deviation, σ_θ, of approximately 2°. These values compared very well with those obtained with actual terrain.

The average maximum allowable random horizon error obtained varied from approximately 0.1° for smoother terrain ($\sigma_T = 50m$) to approximately 0.3° for the roughest terrain ($\sigma_T = 400m$). Results obtained with actual terrain were lower than the average obtained here for the smoother terrains; however, they were on the extremes of the individual case values obtained with pseudo-terrain. Results obtained previously with actual terrain were considerably larger than the average obtained here for the rougher terrains. Part of this difference was felt to be due to the reduced fine-grain variability in the pseudo-terrains which was indicated above. In general, it was felt that the average maximum random horizon error results obtained with pseudo-terrain provide a reasonable average measure of the required error limit. Indications are that it is probably somewhat pessimistic for rougher terrains.

Additional system analysis were performed using the pseudo-terrain. These included analyses of the effect of changes in the horizon range limit, R_L, and the sensed horizon viewing location spacing, ΔS. The effect of the horizon range limit was analyzed by

considering range limits of R_L = 2.5Km, 3.75Km, 5.0Km, and 7.5Km. It was found that it is desirable for position determination performance to use as small a range limit as possible as long as it is large enough to provide horizons with sufficient data content. It was determined that R_L = 2.5Km was too small to provide sufficient data content and thus gross checkpoint misidentifications resulted. Therefore, a range limit of R_L = 3.75Km appears to be a reasonable choice. This choice does result in slightly increased heading determination error with respect to that which would result with larger range limits.

The effect of sensed horizon viewing location spacing was analyzed by considering spacings of ΔS = 200m, 400m, and 800m. The results indicate that sensed horizon spacing should be as small as possible which is no great surprise. Sensed horizon spacing can be increased if larger position and heading errors can be tolerated. However, if the spacing is increased considerably above the minimum 200m assumed, then difficulties are encountered in setting a useful detection threshold. A sensed horizon spacing of as much as 800m is undesirable for this reason.

Also analyzed was the system performance for much higher vehicle altitudes. Analysis was performed using vehicle altitudes of H_A = 0.1Km, 0.5Km, 1Km, 5Km, and 10Km above the maximum terrain height beneath the flight path. In general, results showed that the system performance, in terms of the maximum allowable random horizon error and the position and heading errors obtained with no horizon errors, is insensitive to vehicle altitude over the range of altitudes considered. Cross-track and heading errors apparently increase more at higher vehicle altitudes than at lower vehicle altitudes when random horizon errors are present on horizons generated from rougher terrain.

The effect of vehicle altitude deviations from the planned vehicle altitude was investigated for vehicle altitudes of H_A = 0.5Km, 1Km, and 5Km above the maximum terrain height beneath the flight path. Results indicated that it is feasible to use reference horizons generated for the planned flight path altitude even if the actual vehicle altitude is somewhat different ($\pm$200m in most cases) than planned. This is particularly true if the vehicle altitude is high enough so little shadowing exists for terrain at the range limit.

The final analysis performed was a brief analysis of the improvement in position accuracy which could be achieved by using along-track and cross-track interpolation between the discrete viewing locations of sensed and reference horizons. A simple three point parabolic fit to horizon comparison function data was made in both the along-track and cross-track direcitons. Position error standard deviations were reduced to one-half of the value obtained when no interpolation was used (CEP of approximately55m). Further analysis is required to consider system performance when random horizon errors exist and to establish an optimum interpolation method in this case. This analysis

should also be extended to consider improvement possible in heading determination by using interpolation.

D. GENERAL SUMMARY OF SYSTEM ANALYSIS RESULTS

In general, the simulation analyses have shown that a navigation checkpointing system using horizon correlation is feasible as long as the terrain is sufficiently rough. The sensed horizons should be obtained from terrain within a relatively short range limit (Approx. 4Km) to provide sufficient horizon variability. Performance is affected by the terrain characteristics at the checkpoint location so these locations should not be selected at random.

The checkpointing accuracies obtained with the system are modest but can be improved with closer horizon spacing, additional attention to interpolation, and possibly multiple position determinations in quick sequence with a single sensor or simultaneously with multiple sensors. The major design problem for the sensor is the limitation of random elevation angle measurement errors to relatively small values.

The horizon correlation system provides similar performance over a wide range of altitudes. It is very attractive for low-altitude terrain avoidance flights since a modified version of the terrain avoidance sensor could provide the required sensed horizon data and since sufficiently long horizons are obtained rapidly so considerable flight path flexibility is permitted.

IV. ANALYSES AND DEVELOPMENT IDENTIFIED FOR FURTHER WORK

The analyses to date of the horizon correlation system have established the theoretical feasibility of such a system. They have also indicated further analyses which should be undertaken to more fully describe and develop the system. These analysis projects and initial system verification tests which could be performed by modifying existing radar equipment are indicated in this section. They are discussed in the order which presently appears appropriate for their completion.

A. INITIAL CONCEPT TESTS WITH ACTUAL RADAR DATA

At this point in the system development, it is appropriate to perform initial system verification by correlating sensed horizons obtained by an actual radar sensor with reference horizons generated from topographic data to verify the position determination capability of the horizon correlation system. To provide a lower cost initial test, sensed horizons could be first obtained with a ground based radar located at a high enough elevation with respect to surrounding terrain so horizons could be generated for correlation with reference horizons. This should be followed by generation of sensed horizon data on aircraft flights for verification of horizon correlation checkpointing capabilities.

A couple of existing radar systems have been identified which could be modified to obtain the desired range-limited horizon data. One of these is an amplitude monopulse radar system designed and used by Calspan Corporation for various radar studies. Both van mounted and aircraft mounted versions are available. These radars produce raw radar return data in considerable detail and store it on magnetic tape for subsequent processing with a digital computer. Modifications could be added and computer software developed so this radar test system could be used to generate range-limited horizon profiles. The aircraft which contains the airborne version of the test radar does not contain an accurate inertial navigator and uses the radar itself to help obtain actual aircraft position. Thus it may not be possible to directly obtain good enough actual aircraft position to provide a useful system accuracy determination without test range instrumentation. The elevation beamwidth of the radar is also narrow so it may be difficult to obtain complete horizons on a single scan as necessary.

The second radar system identified for possible modification to obtain actual range-limited sensed horizon data for initial horizon correlation system evaluation is the APQ-148 radar which is an operational radar in the Navy A6 aircraft.[9] This radar is mechanized

to obtain elevation angle measurements with a forward-looking phase monopulse antenna. It has a terrain avoidance mode which displays several range-limited horizons. Thus the radar is already mechanized to obtain the desired range-limited horizon data. This data is presently not digitized or stored. Thus modifications required to the radar to obtain range-limited horizon data for later correlation with reference horizons include analog to digital conversion equipment and computer software to store the range-limited horizon data.

An instrumented APQ-148 radar is mounted on a hilltop at Syracuse Research Corporation. This radar is tied to a general purpose computer and thus has considerable flexibility for test purposes. With the addition of analog to digital conversion equipment on the terrain avoidance data output, it could be used to obtain actual radar data for range-limited horizons in the neighborhood of the hilltop location. These actual sensed horizons could then be correlated with range-limited horizons generated from topographic data for position determination tests of the horizon correlation system. The same radar modification and computer software modifications could then be applied to an APQ-148 radar in an A6 aircraft so range-limited sensed horizon could be obtained on actual aircraft flights. The A6 aircraft contains an accurate inertial navigator which could be used with beacon checkpoints at the start of the data collection portion of a test flight to provide actual aircraft position for determination of horizon correlation checkpointing characteristics.

Of the two radars indicated, the APQ-148 appears to be the most appropriate for the initial system concept verification tests. It should be remembered that the radar has not been specifically designed with the horizon correlation concept in mind so accuracy results which would be obtained would not be optimum. Use of the APQ-148 radar would provide a low cost method of initial system concept test.

B. FURTHER ANALYSIS TASKS

The analyses performed to date on the horizon correlation checkpointing system have indicated a number of further analysis tasks which should be performed to more completely characterize the system. The first task is a study of improvement in position determination accuracy possible with closer spacing of sensed and reference horizons. This study must also consider practical storage limitations on the number of reference horizons which can be stored and development of appropriate methods for obtaining sensed horizons with close spacings.

It has been shown that simple three point parabolic interpolation of the horizon comparison functions can reduce the position determination error by a factor of two when no random horizon errors are present. Other correlation systems use various interpolation techniques. Thus a second task is a detailed analysis of various horizon comparison function

interpolation techniques in the presence of horizon errors to determine the most effective interpolation method and its impact on system position determination accuracy.

Since cross-track position errors and heading errors are highly correlated, it is apparent that greater system accuracy will be possible by using multiple sensed horizons. Therefore, a third task is the definition and analysis of various methods for obtaining and utilizing multiple sensed horizons. This would include definition and analysis of systems using simultaneous horizon sensing (more than one sensor) and sequential horizon sensing. Improvements in system accuracy and in operational limits imposed by terrain roughness should be analyzed and system complexity identified.

A fourth task is the analysis of overall navigation and guidance system performance when horizon correlation is used for checkpointing. For this analysis vehicle dynamics, inertial navigation performance, and guidance philosophy must be assumed so flights encompassing several checkpoints can be simulated to determine if the checkpointing accuracy obtained with horizon correlation is satisfactory to keep an aircraft close to its nominal flight path. Such an analysis would establish tradeoffs between the spacing of checkpoint line arrays and the line array lengths to assure that checkpoints are identified.

The tasks and initial tests described above would lead to the design of a radar sensor and horizon correlation system to perform the navigation checkpointing. Construction and further test of the system would then be in order.

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